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Unravelling the Explosion Mechanism of Core-Collapse Supernovae

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We report here on current progress in understanding the cataclysmic death of massive stars, in course of which the stellar core collapses to a neutron star or black hole and the star itself gets disrupted in a gigantic supernova explosion. Improved numerical tools and the increasing power of modern supercomputers like those of the NIC allow us now to simulate with unprecedented sophistication and detailedness the extremely complex physical processes that take place in the deep interior of a dying star. This has led to the discovery of new phenomena in the supernova core, for example a generic hydrodynamic instability of the stagnant supernova shock against nonradial deformation and the excitation of gravity-wave activity in the nascent neutron star. Both can have a supportive effect on the inauguration of the explosion, the former by improving the conditions for energy deposition by neutrino heating in the postshock gas, the latter by supplying the developing explosion with a flux of acoustic energy that adds to the energy transferred by neutrinos. Here we show recent results of self-consistent, two-dimensional supernova explosion models computed by the Garching group for 9, 11, and 15 solar mass stars.

1 Supernova Explosions and Their Modeling

Supernova explosions mark the death of massive stars with a mass of roughly more than eight times that of the sun. They are among the most powerful and most dramatic events in the universe. While the inner, dense core of the evolved star becomes gravitationally unstable and within seconds collapses to a neutron star, and eventually sometimes to a black hole, most of the stellar gas is ejected with a kinetic energy that equals the radiation loss during the life of the sun. The hot debris of the disrupted star expands into the interstellar space with velocities of several thousand kilometers per second. It shines for weeks nearly as bright as a whole galaxy. This brilliant spectacle, however, is only a wimpy by-product of what happens at the centre of the supernova: The neutron star forming there emits hundred times more than the explosion energy in neutrinos, weakly interacting elementary particles that are abundantly produced in the hot and extremely dense matter of the nascent neutron star. These neutrinos carry away the enormous gravitational binding energy that is released when the moon-sized stellar core with one and a half times the mass of the sun collapses to the hundred times more compact supernova remnant.

Due to the huge energy radiated in neutrinos, these particles have long been speculated to be the driving agent of the stellar explosion. Colgate and White[1] in a seminal paper in 1966 not only proposed gravitational binding energy to be the primary energy source of core-collapse supernovae, but also that the intense flux of escaping neutrinos transfers the energy from the imploding core to the ejected stellar mantle. Nearly twenty years later, Bethe and Wilson[2] were the first who described in detail the way how this might happen, interpreting thereby the physics that played a role in hydrodynamic simulations performed by Wilson.

These pioneering computer simulations of the so-called delayed neutrino-driven explosion mechanism were still conducted in spherical symmetry. The mechanism turned out to be successful only when the neutron star was assumed to become a more luminous neutrino source by convection accelerating the energy transport out of the dense interior. The thus enhanced neutrino emission led to stronger neutrino heating in the overlying layers of the exploding star. Later theoretical studies and the first multi-dimensional computer models, which became available only in the mid 1990's, however, suggested that convection inside the neutron star does not have the necessary big effect. Instead, these simulations demonstrated that the neutrino-heated layers around the forming neutron star are unstable to vigorous convective overturn. This can raise the efficiency of the neutrino energy deposition and thus can have a supportive effect for the supernova explosion. The first such two-dimensional (i.e. axisymmetric) and three-dimensional simulations, however, suffered from a severe drawback: the essential physics of the neutrino transport and neutrino-matter interactions is so complex that it could be treated only in a grossly simplified way, namely by a so-called "grey diffusion approximation". This means that the energy-dependence of the neutrino interactions was ignored and the spatial propagation was approximated by assuming that neutrinos diffuse through the dense neutron star medium until they decouple at the "neutrinosphere" close to the surface of the compact remnant. The historical development of these theoretical studies of the supernova explosion mechanism is resumed in a recent review by Janka et al.[3].

Our project has the goal of advancing the modelling of stellar core collapse to the next level of sophistication. To this end, the Garching group developed a new neutrino transport code (see Rampp and Janka[4]) that is able to describe the propagation of neutrinos through the supernova interior with much higher accuracy than before. It fully accounts for the energy dependence of the problem and for the gradual transition from neutrino diffusion at high densities in the neutron star interior to free streaming of neutrinos in the much more dilute stellar layers far outside of the neutron star. Results of simulations with this latest generation of modelling tools will be presented in Section 3.

A better understanding of the explosion mechanism of core-collapse supernovae is crucial for a large variety of important problems in astrophysics and nuclear astrophysics, but has also very high relevance for fields like particle physics and gravitational physics. What are the properties of supernova explosions and how do they depend on the progenitor star that explodes? Which stars give birth to neutron stars and which ones to black holes when they die? What kind of radioactive elements are synthesized during the explosion and which amounts of them get ejected? Are supernovae the long-sought site of the formation of the most neutron-rich elements like gold, lead, thorium, and uranium in the so-called r-process? What is the signature of neutrino and gravitational-wave emission from collapsing stars, and what can these signals tell us about the physics in the deep interior of the supernova, in particular at the extreme and possibly exotic conditions in the forming neutron star? These and many other questions require a better theoretical insight into the processes that lead to the explosion. Because light is emitted from the surface of the disrupted star and its observation thus yields only indirect information of the events in the centre, the progress in supernova theory largely depends on the possibilities of computational modelling. The extraordinary complexity of the involved processes, which combine multi-dimensional hydrodynamics, relativistic gravity, neutrino and particle physics as well as nuclear physics, poses a major computational challenge. The availability of top-end computing platforms is

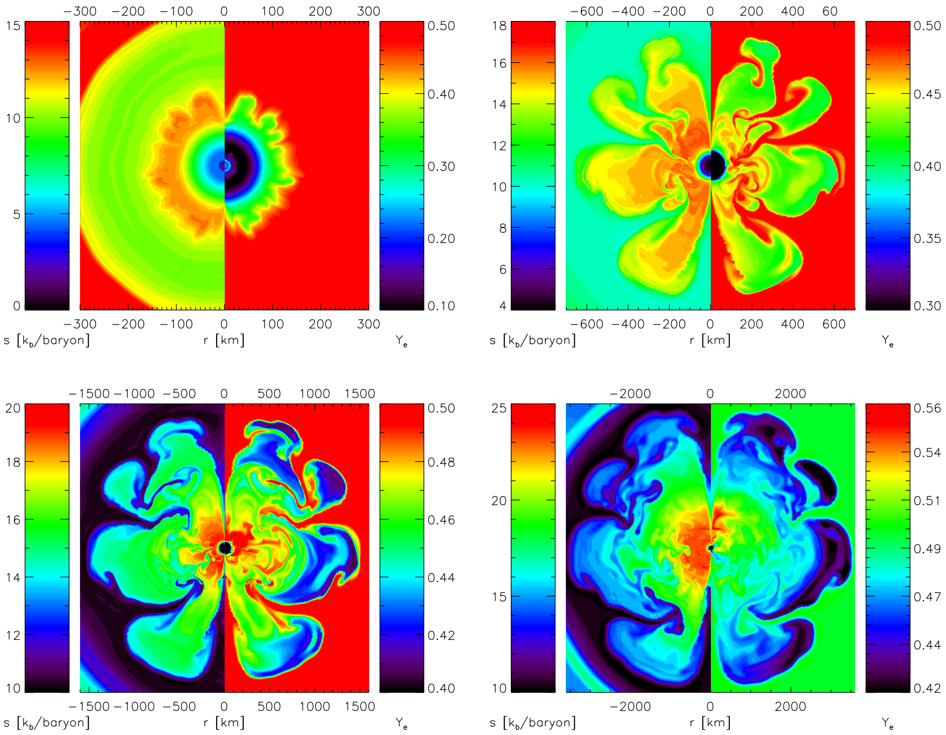

Figure 1. Snaphots showing the gas entropy (left half of panels) and the electron-to-nucleon ratio (right half of panels) for the explosion of a star with about nine solar masses. The plots correspond (from top left to bottom right) to times of 0.097, 0.144, 0.185, and 0.262 seconds after the formation of the supernova shock front and the onset of neutron star formation. Note the different radial scales of the four panels.

a critical issue here. The contributions of the NIC in Jülich to our resources were essential and allowed us in the past years to push forward into unexplored computational territory in modelling supernova explosions.

2 Computational Challenges

The modelling of supernova explosions is one of the greatest computational challenges in numerical astrophysics. Largely different time scales, varying between microseconds and seconds, and length scales, which extend from tens of meters to millions of kilometers, have to be resolved to follow neutrino interactions, nuclear burning, turbulent convection, and sound wave propagation in different regions of the collapsing core and of the ejected outer layers of an exploding star. This is not only computationally extremely demanding: half a second of evolution requires 500.000 time steps and in two spatial dimensions some 10^{18} floating point operations.

The problem is also hard to implement efficiently on massively parallel computers. In particular the neutrino transport module has resisted all such efforts so far and prevents us from the use of distributed memory architectures with many hundreds or thousands of

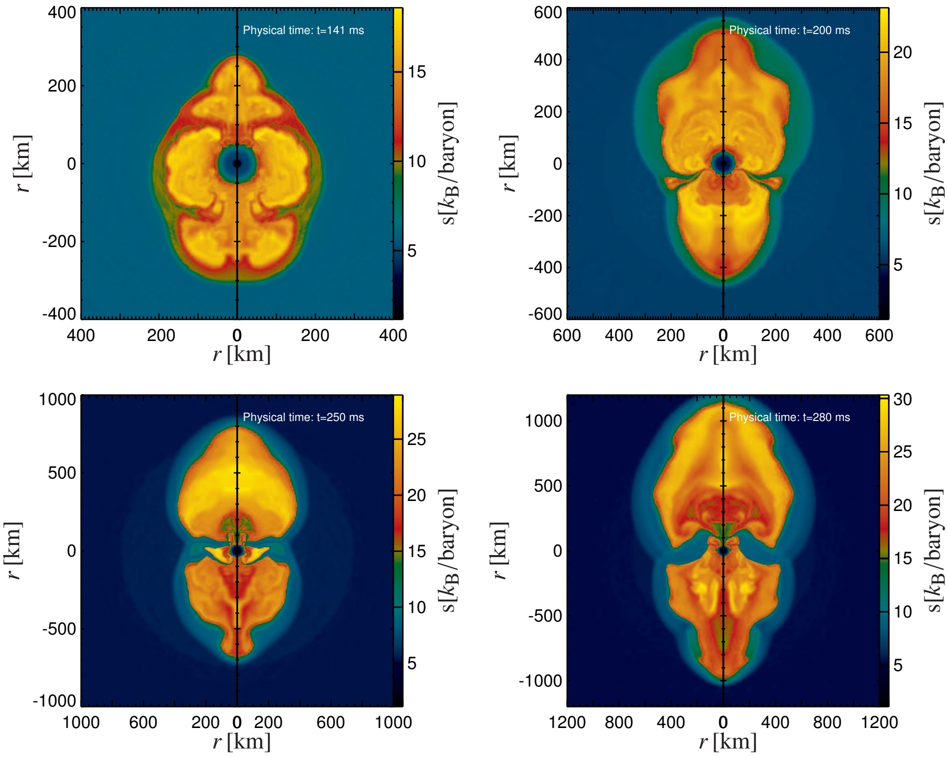

Figure 2. Snapshots of the gas entropy for the explosion of a star with about eleven solar masses at times 0.141, 0.200, 0.250 and 0.280 seconds after the launch of the supernova shock (top left to bottom right). The explosion develops a large asymmetry although the star is not rotating. Note the different radial scales of the four panels.

CPUs. Because the interaction time scales of neutrinos in neutron star matter are extremely short and the neutrino propagation happens with the speed of light after decoupling, the nonlinear transport equations of neutrinos, which as fermions are subject to phase-space blocking effects, need to be solved with fully implicit time stepping. In our current numerical implementation this leads to big, densly filled matrices that have to be inverted several times on every time level of the calculated evolution. This is computationally very expensive and defies easy parallelization. New algorithms, based on iterative multigrid solvers for hyperbolic systems of equations, are currently under development but are not yet available for full-scale supernova calculations. Their use, however, will be unavoidable in future three-dimensional models of supernovae.

The special needs of our current two-dimensional simulations, i.e., shared-memory nodes with powerful CPUs and continuous availability of these nodes for many months, cannot be fulfilled by many supercomputer centres. In particular the IBM p690 *Jump* of the NIC is therefore a highly valuable source of CPU time for our project.

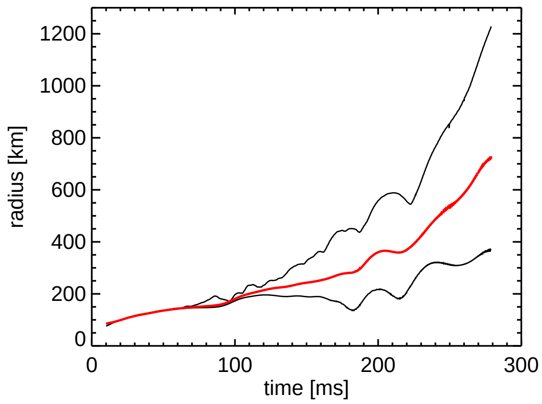

Figure 3. Maximum, average, and minimum radial position of the supernova shock front as functions of time for the explosion of a star with about eleven solar masses. Note the clear signature of several large-amplitude bipolar shock oscillations due to the standing accretion shock instability (SASI) before the blast takes off with an extreme 3:1 deformation.

3 Violent Gas Flows, Neutrino Heating, and Explosion

Our recent results for progenitor stars between 9 and 15 solar masses confirm the viability of the neutrino-heating mechanism for triggering supernova explosions. However, the inauguration of the blast happens not the way expected so far.

The behaviour of supernova progenitors with less than about 10 times the mass of the sun is clearly different from that of more massive stars. The former class of stars develops a core composed of oxygen, neon, and magnesium, not of iron, with an extremely steep density gradient at its surface. This allows the supernova shock front, which is launched at the moment when the neutron star begins to form in the collapsing stellar core, to expand continuously as it propagates into rapidly diluting infalling material. Behind the shock, neutrino heating deposits the energy that powers the explosion. Convective overturn develops in the neutrino heating layer behind the outgoing shock and imprints inhomogeneities on the ejecta, in entropy as well as composition (Fig. 1).

Evolved stars above roughly ten solar masses produce iron cores with a much more shallow density decline outside. Running into this denser material damps the initial expansion of the shock. Moreover, severe energy losses cause the shock to even stall. Different from previous calculations with simple grey neutrino diffusion, our more sophisticated models show that convection is also suppressed in the rapidly infalling matter behind the shock. It cannot become strong enough to give sufficient support for neutrino heating to cause the revival of the stagnant shock. Instead, another kind of nonradial hydrodynamic instability, the so-called standing accretion shock instability (“SASI”), obtains decisive influence on the shock evolution. With highest growth rates of the dipole and quadrupole modes, it leads to violent bipolar shock oscillations. This pushes the shock to larger radii and thus causes secondary convection and improves the conditions for efficient energy deposition by neutrinos, because the gas accreted through the stalled shock stays longer in the heating layer and is able to absorb more energy[5].

The presence of strong SASI oscillations is visible in both of our simulations for 11

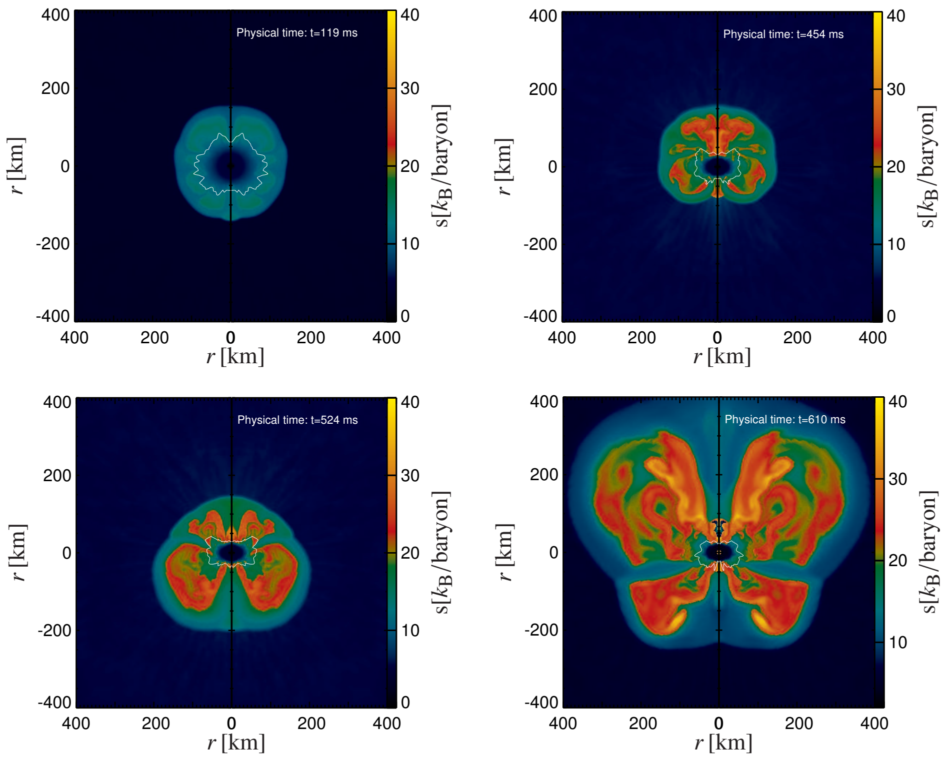

Figure 4. Snapshots of the gas entropy for the explosion of a star with 15 solar masses at times 0.119, 0.454, 0.524 and 0.610 seconds after the launch of the supernova shock (from top left to bottom right). A large north-south asymmetry establishes at the beginning of the explosion. The white line marks the lower boundary of the neutrino-heating region. Note the different radial scales of the four panels.

and 15 solar mass stars and turns out to be decisive for their ultimate explosion (Figs. 2–5). Different from the nine solar-mass star, where convection imposes a high-mode asymmetry pattern on the ejecta (see Fig. 1), the preferred growth of the dipole and quadrupole modes of the SASI leads to a large global anisotropy of the beginning supernova blast in the more massive progenitors[6,7]. The explosion may set in with a significant delay after the neutron star begins to form. For the most massive of the three investigated stars this happens 0.6 seconds later, which is much later than expected.

Our simulations have thus demonstrated the crucial role of the standing accretion shock instability in combination with neutrino heating for initiating supernova explosions. One of the consequences of this mechanism is a global asymmetry of the accelerating shock front and ejected gas. Scheck et al.[8] showed that such large anisotropies can leave the neutron star with a kick velocity that is in the range of the measured eigenvelocities of young pulsars. Moreover, the strongly deformed shock wave triggers mixing instabilities (Richtmyer-Meshkov and Rayleigh-Taylor) at the interfaces of the different composition shells of the exploding star after the passage of the outgoing shock wave. This can lead to large-scale mixing of the chemical elements between the deep interior and the outer stellar

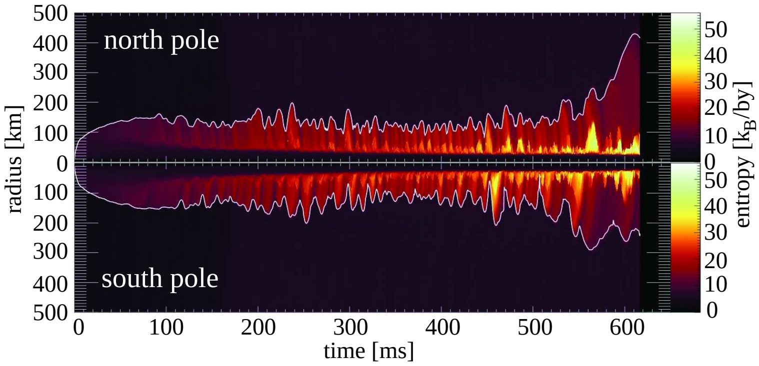

Figure 5. Shock positions near the north pole and near the south pole as functions of time for an exploding star with 15 solar masses. The gas entropy is colour coded. The plot shows the many cycles of quasi-periodic bipolar shock oscillations due to the standing accretion shock instability (SASI).

layers during the explosion, explaining self-consistently a variety of properties observed in well-monitored supernovae like the famous nearby Supernova 1987A[9].

4 Consequences and Future Perspectives

Establishing the progenitor-supernova connection and the final properties of the blast like its energy and the conditions for the formation of chemical elements (e.g., the proton-to-neutron ratio in the ejecta, see Fig. 1) requires many more simulations to be performed and each model to be conducted for many hundred milliseconds beyond the onset of the explosion. Following such a long evolution of highly dynamical behaviour is extremely demanding (also for the accuracy of the numerical scheme) and is one of reasons why these calculations pose a major computational challenge and require the significant amount of supercomputing resources we are also provided with by the NIC (see Section 2).

Recently, Burrows et al.[10,11] have found large-amplitude neutron star oscillations, so-called gravity waves, being excited by the violently turbulent gas flow around the forming compact remnant. In their simulations they saw a sizable amount of acoustic energy being radiated from the ringing neutron star, which thus acted as a transducer of gavitational binding energy released by accreted gas. In fact, this input of sonic energy was sufficient to even initiate the supernova. While this is an interesting alternative to trigger the explosion if neutrino heating fails, we do not observe such a dramatic effect. Yet, we clearly identify the presence of gravity modes in the neutron star. One of our goals for future long-time simulations is therefore a closer investigation of the question whether neutrino-driven explosions might receive an important contribution to their energy from the sound produced by the pulsations of the still anisotropically accreting nascent neutron star.

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